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Correspondence to:
Hyung Wook Park
hwpark@unist.ac.kr

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Experimental investigation of the minimization of uncut fiber length in bidirectional CFRP drilling

Anand Prakash Jaiswal and Hyung Wook Park

Department of Mechanical Engineering, Ulsan National Institute of Science and Technology, Ulsan 44919, Korea

Abstract This research article investigates the minimization of uncut fiber length (UFL) in bidirectional carbon fiber-reinforced polymer (CFRP) drilling through experiments executed using a computer numeric control drilling machine and a titanium nitride-coated drill bit. The cutting conditions, such as the feed rate, spindle speed, and were varied to determine their effects on UFL. Three drilling setups were compared: dry machining, drilling using liquified nitrogen layers, and drilling using ice layers. The results showed that the use of ice improved hole quality and increased drilling efficiency by providing bottom support for the CFRP sheet sandwich, reducing delamination and fiber pull-out. Additionally, the feed rate, cutting speed, and drill geometry significantly influenced hole quality and maximum UFL. Overall, the study sheds light on the usefulness of cooling agents and bottom support for the modification of cutting parameters in bidirectional CFRP drilling.

1. Introduction

The utilization of carbon fiber-reinforced polymer (CFRP) composites has acquired considerable traction in diverse engineering domains owing to their exceptional stiffness, superior weight-to-strength ratio, excellent stiffness, and corrosion prevention [1]. CFRP composites are used in the aerospace, automotive, and marine industries, among various others [2], and show significant promise in replacing traditional materials such as steel and aluminum, especially in applications where lightweight and high strength are required. CFRP composites have unique properties that make them an ideal choice for various applications; however, machining them poses some challenges [3]. Drilling is a commonly used machining process for CFRP composites, e.g., drilling holes for mechanical fastening, joining, and assembly. However, the mechanical characteristics of the CFRP composite are adversely impacted by uncut fibers that develop around the drilled hole [4]. The uncut fiber length (UFL) is an important parameter determining the attribute of drilled CFRP holes in CFRP composites. The longer the UFL, the lower the mechanical properties of the drilled holes. Therefore, it is essential to minimize the UFL to ensure the desired mechanical properties of the final product [5]. Researchers have recently focused on reducing the UFL in CFRP composites during drilling. Several methods have been proposed to minimize the UFL, including drilling parameter optimization, tool design, and cutting fluid application. However, optimizing drilling parameters remains the most effective approach for minimizing the UFL in CFRP composites [6, 7]. This approach involves selecting the appropriate drilling conditions, to reduce the UFL, and adjusting variables like feed rate, spindle speed, and tool diameter. Feed rate is the rate at which the drill bit is fed into the material, whereas spindle speed refers to the drill bit's rate of rotation [8], and drill diameter refers to the diameter of the drilling tool used for drilling. The selection of optimal drilling parameters is crucial for minimizing the UFL and improving the mechanical properties of drilled holes [9]. Therefore, several studies have focused on investigating the drilling of CFRP components, focusing specifically on minimizing the UFL. The drilling parameters, including the feed rate, cutting speed, and drill geometry, are key areas of focus in reducing the UFL. Kilickap et al. [10] examined the impact of cutting conditions on UFL in the drilling of CFRP composites; their results showed that the UFL was decreased by using a low feed rate and fast cutting speed and improved the superiority of drilled holes. In addition to drilling conditions, drill geometry can also affect the UFL. Bayraktar et al. [11] examined the impact of drill tip angle on the UFL in the drilling of CFRP composites; the results demonstrated that a smaller drill tip angle reduced the UFL and improved the superiority of drilled holes.

The drilling technique is another consideration concerning the UFL. In a study by Davim and Reis [12], a low feed rate and small drill diameter were responsible for reducing delamination and improving the quality of drilled holes in a CFRP composite. Several studies have been conducted to investigate the factors affecting UFL during the drilling of CFRP materials. Krishnaraj et al. [13] in unidirectional CFRP materials, the causes of drilling feed rate, tool rotational cutting speed, and drill tooltip angle on UFL were examined; they reported that higher cutting speeds and feed rates reduced the UFL, while a drill point angle of 90° produced the shortest UFL. Similarly, Shetty et al. [14] examined how UFL in bidirectional CFRP materials was affected by cutting parameters such as drilling feed rate, tool rotational cutting speed, and drill tip angle. They reported that a lower feed rate and higher cutting speed resulted in a shorter UFL, while a drill point angle of 130° produced the shortest UFL. Bosco et al. [15] carried out an experimental investigation of how tool geometry affects UFL while drilling CFRP materials. They claimed that the use of a tool with a small, included angle and a sharp edge can significantly reduce the UFL and delamination. Other researchers have investigated the effect of drilling techniques, such as ultrasonic-assisted drilling and vibration-assisted drilling, on UFL reduction. Chen et al. [16] examined the effect of vibration-assisted drilling on UFL reduction in CFRP materials and reported that it can improve hole quality and reduce UFL. In a study that investigated the minimization of the UFL in unidirectional CFRP drilling conducted by Karataş et al. [17], a combination of experimental and numerical methods was used to verify the effects of tool geometry and cutting parameters on the UFL. They found that the helix angle of the drill bit had the most significant effect on the UFL; specifically, increasing the helix angle reduced the UFL. In another study, Shu et al. [18] analyzed how tool wear affected UFL during unidirectional CFRP drilling; an acoustical emission method was used to supervise the tool wear and UFL. They found that the UFL increased with the tool wear, leading to a reduction in the mechanical properties of the material. Xu and Mansori [19] studied how drill bit angle affected the UFL, using a special drill bit with a variable angle to drill bidirectional CFRP laminates; they found that increasing the drill bit angle significantly reduced the UFL. Xu et al. [20] studied how bidirectional CFRP drilling settings affected the UFL, using a grouping of investigational and numerical methods to determine the influences of feed rate, CFRP cutting speed, and drill bit tool diameter on the UFL. They found that the cutting speed had the most substantial influence on the UFL; increasing the cutting speed reduced the UFL. In summary, the literature suggests that the UFL can be reduced in CFRP drilling through the optimization of cutting parameters, tool geometry, and the use of drilling techniques such as ultrasonic-assisted drilling and vibration-assisted drilling. However, there is still a need for further experimental investigation to identify the optimal drilling parameters and techniques that can minimize the UFL and increase the condition and strength of drilled holes in CFRP materials [21]. The optimization of drilling parameters and techniques can significantly shorten the UFL and improve the superiority of drilled holes in CFRP components.

Therefore, the research aimed to investigate the optimal drilling conditions and techniques for minimizing the UFL in bidirectional CFRP drilling. The experimental investigation included drilling tests in various drilling variables, such as the feed rate, drill tool diameter, and spindle speed, which were changed. The UFL was measured using an optical microscope to analyze the effects of the drilling parameters. In the experimental investigation, bidirectional CFRP composite plates, made from epoxy resin and unidirectional carbon fibers, were used. The unidirectional CFRP composite plates had a fiber orientation of 0° and 90°. The drilling tests were conducted using a titanium nitride (TiN) drill bit (diameter: 3 mm). The drilling parameters were varied in the experiments, and the UFL was measured for each combination of drilling parameters. The experimental results showed that the UFL is impressed by the drilling parameters. In bidirectional CFRP drilling, a faster spindle speed and a slower feed rate led to a shorter UFL. Additionally, smaller drill diameters produced shorter UFLs. A comparative study of three drilling techniques was also performed. The findings of this research provide insight into the optimization of drilling conditions to minimize the UFL in CFRP composites. The optimization of drilling parameters can result in better mechanical properties of drilled holes in CFRP composites, leading to improved performance and reliability of various engineering applications.

2. Experimental investigation and setup

An experimental investigation was conducted to minimize the UFL in bidirectional CFRP drilling. The experiments were performed using a computer numeric control (CNC) drilling machine (Fa-402DSN; Dongbu Lightec) and a 3-mm-diameter TiN-coated Kennametal drill bit (B041A03000CPG KC7325). The workpiece was manufactured by SK Chemicals (Korea) having sheet dimensions of 100 mm × 100 mm × 3 mm, and a fiber orientation sequence of 90° or 0°, for up to 10 layers. Table 1 shows the cutting parameters of spindle speed and feed rate were varied to determine their effects on the UFL. These cutting parameters were chosen in accordance with the manufacturer's suggestions and earlier academic studies in the area. With the combination of these machining conditions, sets of experiments were repeated eight times to obtain an accurate result. The experimental setup included a CFRP plate, drill bit, spindle, drilling jig, and liquified nitrogen (LN) system. The

Table 1. Specification of the tool, workpiece, and machining parameters.

Workpiece specification	
Dimension	100*100*3 mm
Fiber orientation	90°, 0°, …., 10S
Number of layers	10
Tool specification	
Tool diameter	3 mm
Primary cone angle	118°
Helix angle	30°
Machining parameters	
Feed rate	100 and 150 mm/min
Rotational speed (RPM)	3000, 5000, and 7000

CFRP plate was clamped to the machine bed, and the drill bit was placed on the spindle.

The experimental process was performed using three drilling techniques: (i) CFRP drilling by dry machining, (ii) CFRP drilling via sandwiching the CFRP with LN, and (iii) CFRP drilling via sandwiching the CFRP with ice. The three techniques are described in detail in the following.

(i) CFRP drilling by dry machining: Dry machining is a cutting process that involves the use of cutting tools without any coolant or lubricant. This method has gained increasing attention as an eco-friendly and cost-effective alternative to conventional wet machining. However, its application to CFRP drilling is still limited, and further investigation is necessary to assess its feasibility and optimize its parameters. In our experimental investigation of CFRP drilling by dry machining, several key parameters were studied, including the CFRP drilling feed rate, cutting speed, drill geometry, and cutting tool material. The experiments were conducted using a CNC drilling machine equipped with a TiN-coated drill bit. The maximum UFL and hole quality were significantly impacted by the tool feed rate and CFRP cutting speed. The drill geometry also played an important role with the goal of minimizing delamination and fiber pull-out, the use of a point angle of 118° being the most effective. For the comparative study, we performed conventional CFRP drilling under dry machining conditions. The experiment was performed using feed rates of 100 and 150 mm/min with spindle speeds of 3000, 5000, and 7000 rpm.

(ii) CFRP drilling with LN: LN has a low temperature (−196 °C) and can quickly absorb the heat generated during drilling, thus preventing excessive heat build-up, and minimizing the risk of delamination because it changes the fiber's properties for a certain amount of time. With LN use, the fiber sheet was converted from a ductile state to a more brittle structure, which reduced the length of the uncut fiber in CFRP drilling. The drilling of the CFRP sheet occurred inside an LN tank. The CFRP sheet was placed in the LN tank for 1 hour and was then allowed to cool to approximately −196 °C. Drilling was performed with a custom-designed jig. LN filled the jig up to 10 mm of the height of the jig. After filling the bottom of the jig with LN, the CFRP sheet was attached. LN then filled the tank again to a height of 10 mm above the CFRP sheet, such that the CFRP sheet was sandwiched between LN layers.

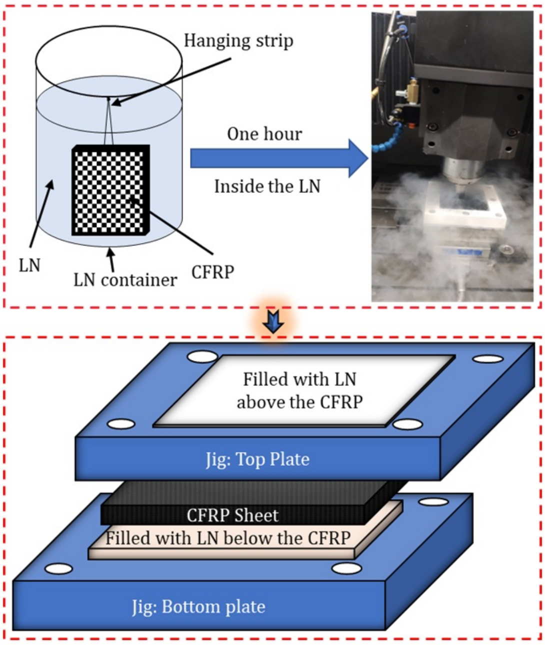

Fig. 1. Preparation of the CFRP drilling setup - 1: sandwich of CFRP with LN.

Fig. 1 illustrates the process of creating LN layers encompassing the CFRP sheet for drilling. Due to the rapid cooldown with this process, a cleared hole was produced as the material changed from a brittle structure to a more ductile form without the uncut fiber. Thus, the CFRP material was effectively sandwiched between two layers of LN, fed by a continuous flow of coolant during the drilling process.

Drilling experiments with various drilling parameters are typically part of experimental research employing the LN technique (e.g., feed rate, cutting speed, and drill bit geometry), in an attempt to identify the optimal drilling conditions for achieving high-quality holes with minimal damage to the CFRP material. A possible method to enhance hole quality, lessen tool wear, and boost drilling efficiency is the use of LN as a coolant while drilling CFRP materials. However, the effectiveness of this approach can be influenced by several factors, including material properties, drilling parameters, and cooling system design. Therefore, further experimental investigations may be required to fully understand the benefits and limitations of this approach.

(iii) CFRP drilling with ice: Fig. 2 depicts the experimental setup for CFRP drilling through ice. The CFRP sheet was positioned in a bottom jig filled with water. A refrigerator was used to create an ice layer of 15 mm in thickness on one side of the sheet (in the bottom jig). After 12 hours (hr), the CFRP sheet was flipped over, and the process was repeated to create an ice layer on the other side. Here, it was important to ensure that the ice layer had solidified and was ready for drilling. Once the sandwich setup was created, we drilled the CFRP sheet via the CNC machine.

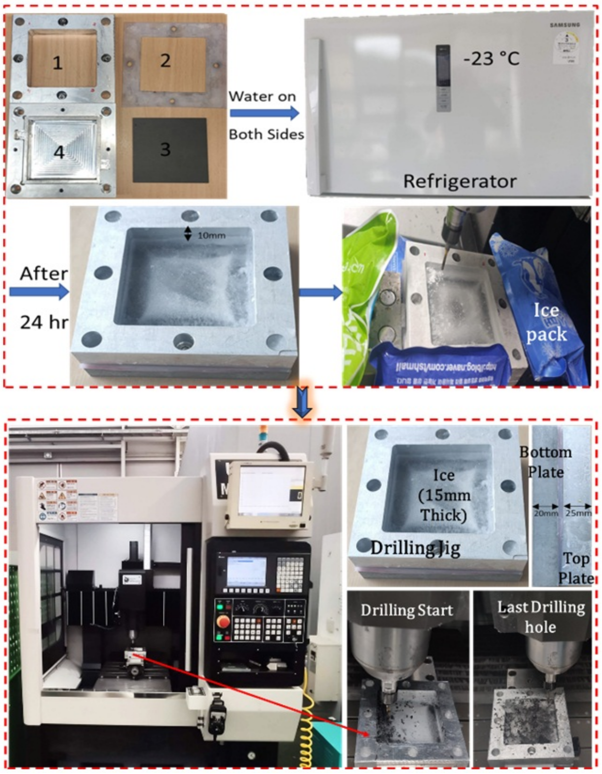

Fig. 2. Preparation of the CFRP drilling setup - 2: sandwich of CFRP with Ice.

At the time of machining, the bottom jig solid ice layer provided proper bottom support to the bottom of the CFRP sheet. Notably, this support was temporary, in that the ice layer easily melted away after machining. Additionally, the jig used a packing rubber washer, which protected the linkage of the water before conversion to ice. The uncut length refers to the length of the fibers that were not cut during the drilling process. In this experiment, the UFL varied from 0 to 1598 μm, meaning that some fibers were cut completely while others were partially cut. Thus, this experiment provided insight into the effectiveness of the drilling process and potential damage imparted to the CFRP fibers. Notably, more of the drilling hole was cleared without uncut fiber. This suggests that the ice layer on both sides of the CFRP sheet helped reduce the amount of damage to the fibers during drilling. Thus, this experiment provides valuable information on the drilling of CFRP with an ice layer, which can be used to optimize the drilling process for CFRP composites in various applications.

3. Results and analysis

3.1 CFRP drilling error measurement in terms of maximum uncut fiber

When drilling into a CFRP material, the goal is to create a hole without damaging the fibers, as any damage to the fibers can weaken the overall structural stability of the substance. However, due to the anisotropic nature of CFRP, the drilling process can cause delamination, fiber pullout, or other damage to the material. The maximum UFL is the longest continuous length of carbon fiber that remains intact after drilling. This measurement is typically taken at the edge of the hole, where the fibers are most likely to be damaged. A smaller maximum UFL indicates a greater level of damage to the material and thus a higher level of drilling error. Measuring the maximum UFL can be done visually or with the help of an imaging tool digital microscope. The measurement can also be used to evaluate the effectiveness of different drilling techniques and parameters (e.g., drill speed and feed rate) in minimizing drilling error and preserving the integrity of the CFRP material.

In this study, we used one conventional and two advanced CFRP drilling processes. The convention drilling process was done for a comparative study with the other two. We used various machining parameters for optimizing the machining conditions in terms of the feed rate in the Z-direction and tool rotational speed. Fig. 3 describes the after-drilling microscopic image under various conditions, which indicates the optimum drilling process in terms of the minimum UFL. Conventional CFRP drilling (dry machining) provided a longer uncut fiber in all machining conditions compared with the other two techniques. CFRP drilling with LN resulted in a shorter uncut fiber compared with that obtained using dry machining. Moreover, CFRP with ice provided better results than those obtained using the other two techniques under all machining conditions.

Several process variables, including the drilling feed rate, cutting speed, and tool geometry, must be tuned in order to drill the CFRP. One critical parameter that affects the drilling process is the maximum UFL. The UFL is the length of the carbon fiber that remains uncut after drilling. The longer the UFL, the higher the risk of delamination and tool wear. Therefore, it is essential to determine the maximum UFL for a given set of drilling conditions. In this study, the maximum UFL was determined for the three drilling techniques (dry machining, with LN, and with ice) and two feed rates of 100 and 150 mm/min. Dry machining, in which no coolant was used during the drilling process, was also included as a reference point. The values for dry machining in Fig. 4 represent the maximum UFL under this condition. As expected, the maximum UFL was relatively high for dry machining, ranging from 1587 to 1938 μm depending on the feed rate. The reason for the high UFL was that the lack of coolant led to high friction and heat generation, which can soften the matrix material, thus allowing the fibers to deform and move aside instead of being cut. The use of coolant can help reduce the UFL and improve the excellence of the drilled CFRP hole. In Fig. 4, the two modified drilling methods are considered, in which the CFRP sheet was sandwiched between LN or ice layers. In the LN setup, LN flowed over the upper and lower surfaces of the CFRP sheet during the drilling process. The low temperature provided by the LN reduced the heat generated during cutting for improved tool life.

In contrast, in the ice setup, the ice layers provided direct support to the top and bottom sides of the CFRP sheet during

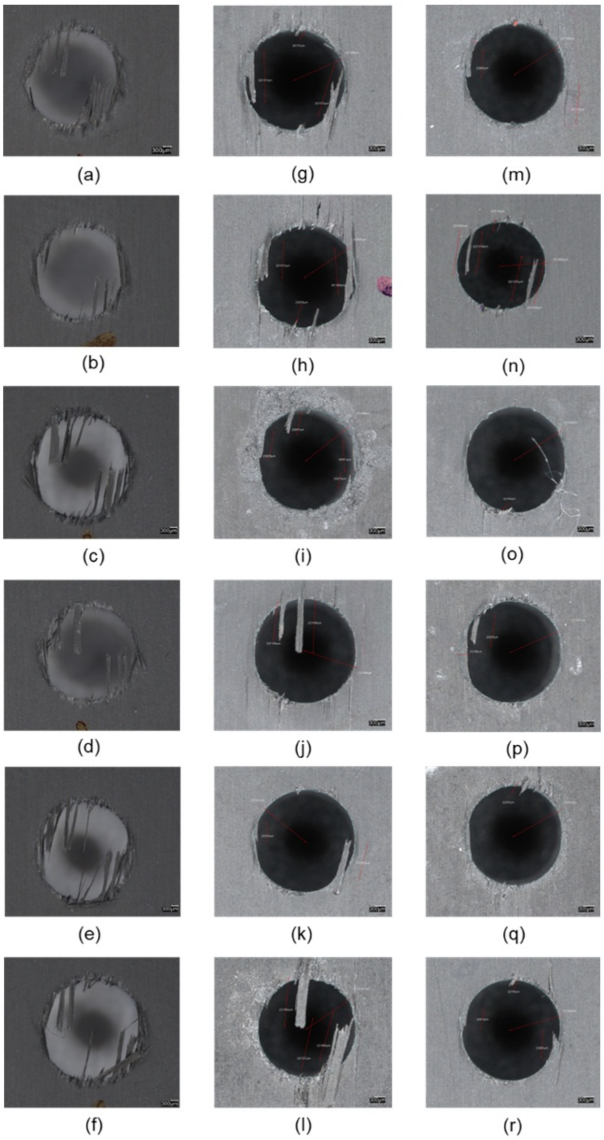

Fig. 3. Fundamental study of machining parameters on the various drilling methods with 3 mm drill diameter (a-f) dry machining; (g-l) sandwich of CFRP with LN_1; (m-r) sandwich of CFRP with Ice_2. (a, g, m): drilling with a rotational speed of 3000 RPM and feed rate of 100 mm/min; (b, h, n): rotational speed 3000 RPM and feed rate 150 mm/min; (c, i, o): rotational speed 5000 RPM and feed rate 100 mm/min; (d, j, p): rotational speed 5000 RPM and feed rate 150 mm/min; (e, k, q): rotational speed 7000 RPM and feed rate 100 mm/min; (f, l, r): rotational speed 7000 RPM and feed rate 150 mm/min.

drilling. The ice layers cooled the drill bit and the hole, thus improving the surface quality of the drilled hole. It was evident that the CFRP drilling process could be optimized by identifying the appropriate method and drilling parameters. For instance, with a feed rate of 150 mm/min, the maximum UFL was reduced from 1938 μm in dry machining to 963 μm with LN and 430 μm with ice. At a drilling feed rate for the CFRP drilling of 100 mm/min, the maximum UFL was reduced from 1612 μm with dry machining to 772 and 529 μm with LN and ice drilling, respectively. The reason for the reduction in maximum UFL

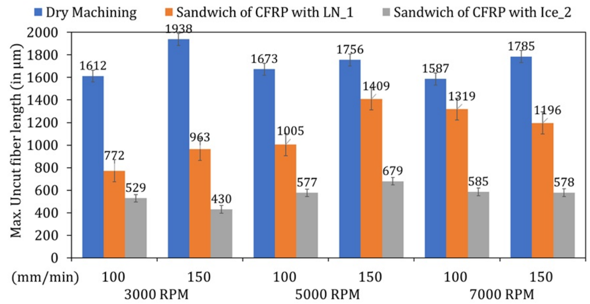

Fig. 4. Maximum uncut fiber length (UFL) at various machining methods with different feed rates and rotational speeds.

with the coolant and support techniques is that these methods briefly change the fiber's properties during cutting. The softening of the matrix material with drilling, which allows the fibers to deform and move aside instead of being cut, is offset by the heat reduction provided by cooling. The heat reduction also helps to reduce wear on the cutting tool, which further improves the quality of the drilled hole.

In summary, the maximum UFL is an essential parameter to consider when drilling CFRP. The UFL can be reduced by changing the cooling properties (from ductile to brittle) using LN or ice drilling methods, and by providing support to the sheet during drilling (drilling with ice technique), as described. The precision of the drilled hole can be enhanced, and the chance of delamination can be decreased by lowering the UFL.

Overall, the experimental investigation demonstrated the potential of dry machining for CFRP drilling, provided that the appropriate cutting parameters and tool selection were used. However, further research is needed to optimize the cutting conditions and evaluate the long-term performance and economic feasibility of dry machining compared to wet machining.

The average maximum feed force is an important performance measure that indicates the force required to drill a hole in the CFRP. The results presented in the figure indicate the average maximum feed force values varied significantly with various modifications to the processing variables, including feed rate and rotating speed. Placing the CFRP between LN or ice layers significantly reduced the average maximum feed force value, thus leading to better drilling performance.

3.1.1 ANOVA (analysis of variance) analysis

Regarding the appropriate outcome of the CFRP drilling experiment concerning the maximum uncut fiber length, the results of the analysis of variance (ANOVA) analysis are presented in Table 2.

The ANOVA results indicate a significant difference between the means of the groups, as indicated by the remarkably low p-value (1.53092E-08), which is substantially smaller than conventional significance levels, such as 0.05. Additionally, the F-value (75.11664843) is notably higher than the critical F-value (3.682320344). Therefore, it can be concluded that there is a significant difference between the means of at least two groups.

Consequently, it is reasonable to infer that the researchers

Table 2. ANOVA analysis for the maximum uncut fiber length.

Groups		Sum		Average	Variance
Dry machining		10351		1725.2	16889.4
Sandwich of CFRP with LN_1		6664		1110.7	57470.7
Sandwich of CFRP with Ice_2		3378		563	6641.2
Variation		SS		DOF	MS
Between groups		4056361		2	2028180
Within groups		405006.2		15	27000.41
Total		4461367		17	
P-value	1.53E-08	F	75.2	F-critical	3.68

SS: sum of squares; DOF: degree of freedom; MS: mean of squares.

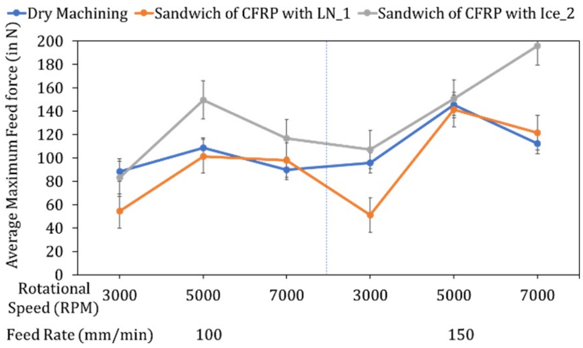

Fig. 5. Maximum average force at various methods and parameters.

likely rejected the null hypothesis, which posited no difference between groups, in favor of the alternative hypothesis, which suggests a significant difference between at least two groups.

3.2 Effect of drilling feed force

It is vital to consider the impact of numerous processing influences, such as feed rate, rotating speed, and tool geometry, to optimize the CFRP drilling process. In this context, the average maximum feed force is an important performance measure that indicates the force required to drill a hole in the CFRP. Fig. 5 displays the average maximum feed forces for CFRP drilling at various feed rates and spindle speeds with and without the use of LN cooling ice backup techniques, with and without the use of LN and ice cooling methods. The average maximum feed force values are given in Newtons (N), and the values are determined through the experimental results.

The average maximum feed force values vary significantly with changes in the processing parameters. For instance, when the rotational speed increased from 3000 to 7000 rpm, the average maximum feed force values increased for both dry machining and machining with the LN and ice layers. This increase in feed force was due to the increase in cutting speed, which causes more heat generation and material removal, leading to a higher force requirement. Similarly, when the CFRP drilling feed rate improved from 100 to 150 mm/min, the average maximum feed force values increased for both dry machining and the LN and ice drilling methods. This increase in feed force was due to the increase in the amount of material being removed per unit of time, leading to a higher force requirement.

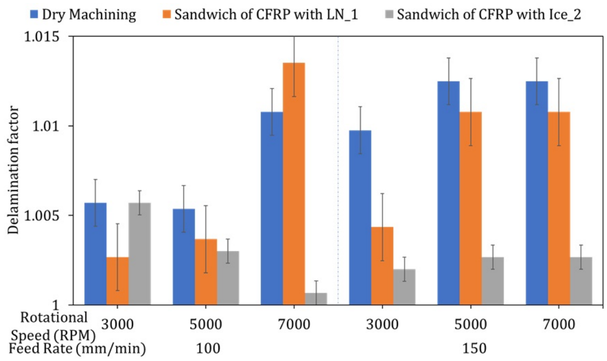

Fig. 6. Exit hole delamination factor of CFRP drilling at various parameters.

Comparing the results of dry machining with those obtained using the LN and ice drilling methods, it is clear that both cooling and providing bottom support significantly reduced the average maximum feed force values. With these methods, the amount of heat is reduced, along with the potential for thermal damage, thus leading to a lower force requirement. Moreover, the results showed that sandwiching the CFRP between ice layers lowered the average maximum feed force values compared to the LN sandwich method. This is because the ice provided both cooling and better bottom support than the LN flowing layers. The average maximum feed force is an important performance measure that indicates the force required to drill a hole in the CFRP. The results presented in Fig. 5 show that the average maximum feed force values varied significantly with various modifications to the processing variables, including feed rate and rotating speed. Placing the CFRP between LN or ice layers significantly reduced the average maximum feed force value, thus leading to better drilling performance.

3.3 Delamination factor

This study measured the delamination factor from the exit hole layer of the CFRP using two machining parameters: the tool rotational speed and drilling feed rate. The degree of damage or separation that develops at the interface between the layers of the composite material during machining is referred to as the delamination factor. It is an important factor to consider when machining composites, as excessive delamination can compromise the strength and durability of the final product. The feed rate and rotational speed are two important machining parameters that affect the factor of delamination. The rate is the feed rate at which the cutting tool moves along the workpiece, and the rotational speed is the speed at which the cutting tool spins. Our results suggest that the type of interlayer material used to sandwich the CFRP layer has a significant effect on the factor of delamination. The findings demonstrated that the CFRP surrounded by LN layers had the lowest delamination factor values, whereas the CFRP sandwiched between ice layers had the highest values for the delamination factor. Additionally, rising the feed rate and declining the rotational speed generally led to a lower value for the delamination factor. However, the specific effects of these machining parameters varied depending on the type of interlayer material used.

4. Conclusions

This research aimed to minimize the UFL in bidirectional CFRP drilling using various setups. Experiments were conducted using a CNC drilling machine and a TiN-coated, 3-mm-diameter Kennametal drill bit. The effects of two cutting factors, feed rate, and spindle speed, on the UFL were investigated. Three CFRP drilling setups were compared: dry machining, LN layer coolant, and ice layer coolant. Dry machining involved using cutting tools without any coolant or lubricant, while LN and ice drilling utilized cooling agents that sandwiched the material between flowing liquid and solid layers, respectively. The experimental investigation comprised drilling tests with different parameters to determine optimal conditions for achieving high-quality holes with minimal CFRP material damage. Utilizing LN and ice layers as coolants and bottom support showed the potential to increase drilling efficiency by reducing hole quality and delamination while enhancing feed force efficiency. However, further experimental investigations are necessary to fully understand the benefits and limitations of these approaches.

A limitation of this study is its focus on CFRP materials, implying that the results may not directly apply to drilling other material types. Different materials may possess distinct properties influencing the optimal drilling parameters and cooling agent effectiveness.

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Anand Prakash Jaiswal is presently a Ph.D. candidate specializing in Mechanical Engineering at the esteemed Ulsan National Institute of Science and Technology (UNIST) in South Korea. His current academic pursuit involves the attainment of a doctoral degree in the field of machining of Carbon Fiber Reinforced Polymer (CFRP) materials at UNIST. The focal point of his scholarly endeavors revolves around analytical modeling and the optimization of machining techniques applied to composite materials.

Hyung Wook Park is an esteemed Professor of Mechanical Engineering at Ulsan National Institute of Science and Technology (UNIST), South Korea. He holds a Ph.D. from Georgia Institute of Technology, USA, and received his B.S. and M.S. degrees from Seoul National University, Korea. Professor Park's research interests encompass machine tools, metal cutting processes, non-traditional machining techniques, surface texturing using metal cutting, FEM modeling, and advancements in robot manufacturing. His contributions significantly enrich the academic and scientific community, enhancing knowledge and understanding in these critical areas of research.